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A review of power electronics interfaces for distributed energy systems towards achieving low-cost modular design

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ABSTRACT

Due to increased attention towards clean and sustainable energy, distributed energy (DE) systems are gaining popularity all over the world. Power electronics are an integral part of these energy systems being able to convert generated electricity into consumer usable and utility compatible forms. But the addition of power electronics adds costs to the DE capital investments along with some reliability issues. Therefore, widespread use of distributed energy requires power electronics topologies that are less expensive and more dependable. Use of modular power electronics is a way to address these issues. Adoption of functional building blocks that can be used for multiple applications results in high volume production and reduced engineering effort, design testing, onsite installation and maintenance work for specific customer applications. In this paper, different power electronics topologies are reviewed that are typically used with distributed energy systems. The integrated power electronics module (IPEM) based back-to-back converter topologies are found to be most suitable interface that can operate with different DE systems with small or no modifications. Also the requirements for a hierarchical control structure with standardized power and communication interfaces are addressed in the paper along with some discussion on future design possibilities for the IPEM-based power electronics topologies. It is expected that modular and flexible power electronics and standardized controls and interfaces, will provide commonality in hardware and software for the power electronics interfaces, thus will enable their volume production and decrease their cost share in distributed energy applications.

Contents

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1. Introduction

Distributed energy (DE) systems have already made a significant impact on the energy market and will certainly affect energy scenarios in the near future. These DE systems include but are not limited to photovoltaics (PVs), wind, microturbine, fuel cells, and internal combustion (IC) engines [1]. In addition, several energy storage systems such as battery and flywheel are under consideration for DE to harness excess electricity produced by the most efficient generators during low loading. This harvested energy can be released onto the grid, when needed, to eliminate requirement for high-cost generators. The inclusion of storage capabilities in the distributed generation system actually provides the user with dispatchability of its distributed resources which generally are renewable energy sources, like PV and solar, that have no dispatchability without it. All these DE technologies require specific power electronics (PE) capabilities to convert the power generated into useful power that can be directly interconnected with the utility grid and/or can be used for consumer applications. Because PE interfaces function similarly, the development of scalable, modular, low cost, highly reliable PE interfaces will improve the overall cost and durability of distributed and renewable energy systems.

Although most of DE systems are not new in technological respect, they are receiving increased attention today because of their ability to provide combined heat and power, peak power, demand reduction, backup power, improved power quality, and ancillary services to the power grid. The visibility of renewable energy sources are increasing significantly due to common concerns about fossil fuel scarcity, increased pollution, weakened national security, and higher production of greenhouse gases related to the conventional power plants. In the United States, the adoption of Renewable Portfolio Standards by several state governments is also creating a big thrust to generate a certain percentage of energy produced by renewable energy sources. Even with all the benefits renewable energy has to offer, the decision on DE installations are still largely dependent on initial capital cost. Although power electronics are the integral part of most of the DE technologies and can provide significant benefits [2], they can be very costly. In Fig. 1, a representative chart is given that compares the average PE costs in terms of percentage of total capital costs for four DE systems. It is evident from the figure that the PE can contribute up to 40% of the total capital cost [3].

Therefore the improvement of the DE economics strongly requires decreased costs for the power electronics. Another important aspect to the life-cycle cost of the DE systems is reliability. Many of the power electronics used for DE applications have a low reliability and typically operate less than 5 years before a failure occurs.

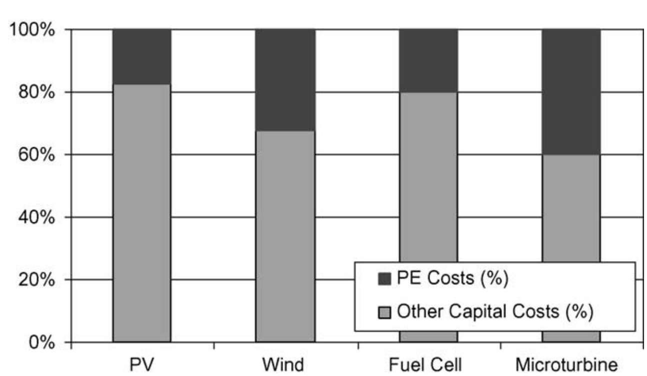

Fig. 1. Power electronics costs compared to total capital costs for DE systems.

In the United States, California Energy Commission Public Interest Energy Research (PIER) program has taken the initiative to implement projects to accelerate the use of DE systems, in part by addressing the cost and reliability of the one common element of all of the distributed and renewable technologies–the power electronics interface (PEI). According to a survey conducted by Navigant Consulting under this initiative had found that from the commercialization perspective, the key business needs for DE power electronics are reducing costs and improving reliability [4]. Associated with these cost and reliability issues, three major technology challenges exist when discussing power electronics for DE applications [4].

- There is a lack of standardization and interoperability among power electronics components and systems. This increases the cost of manufacturability and reduces volume and reliability.
- Power electronics devices must be modular and scalable. This will simplify applications and designs, leading to increased use; higher production volumes will lower costs and improve performance.
- Current research focuses on power electronics subsystems and component rather than the DER system package. Improvements in the system package are urgently needed for DER.

Power electronics building block (PEBB) is a known concept for designing modular PE systems that incorporates integration of power devices, gate drives, and other components to functional blocks [5]. Adoption of functional building blocks that can be used for multiple applications results in high volume production, and reduced engineering effort, design testing, onsite installation and maintenance work for specific customer applications. The value of integration can be enhanced with standardization of interfaces of the building blocks, control or protections requirements [6].

The purpose of this paper is to provide a consolidated resource that describes the most common power electronics interfaces for DE applications and outlines possible power electronics topologies that will lead to a low cost, reliable power electronics interfaces. Various power electronics topologies are discussed for different DE systems to find a generalized topology that can be used for different DE applications with very small or almost no modification. The objective for such generalized power electronics topologies is to apply the PEBB concept into designing a power electronics interface that is flexible to work with different sources; scalable to meet different power requirements; with modular design, lower cost, and improved reliability; and will improve the overall cost and durability of distributed and renewable energy systems.

Also discussed in this paper are the challenges that must first be overcome to reach the goal of modularity. One challenge lies in defining the power and communication interfaces. The power connection interfaces must be simple enough for the common consumers to accomplish installation. Standardization is also required for the communication interfaces between modules, packages and controllers. IEEE standards do not currently address this issue, so there is no standard for communication between different products [6,7]. To have complete modular power electronics interface systems, the control software must be functionally divided into hierarchical levels and interfaces must be standardized between levels, so that the application software becomes independent of the hardware specifications of power stage; and products from different vendors can communicate and work with each other [8]. Furthermore, if both sides of an interface support device self-identification and system resources assignment, then the so-called plug-and-play implementation is feasible for future PEI systems.

2. Power electronics for distributed energy systems

The design of the power electronics depends on the specific energy source or storage application. The power electronics interface accepts power from the distributed energy source and converts it to power at the required voltage and frequency [9]. DE systems that generate AC output, often with variable frequencies, such as wind, microturbine, IC engine or flywheel storage need AC–DC converters. For DC output systems like PV, fuel cells, or batteries, a DC–DC converter is typically needed to change the DC voltage level. The DC–AC inverter is the most generic for all the DE systems and converts a DC source to grid-compatible AC power. Additionally, for the storage systems, bidirectional flow of power between the storages and the utility is required. The most common power electronics interfaces for DE applications are discussed next where it is assumed that the DE systems are connected to the three-phase utility and galvanic isolation is required between the DE systems and the utility. There are some transformer-less configurations available in literature that can be used for the DE systems. But such topologies are more for the European countries and Japan where system grounding is not mandatory for the DE inverters. In the United States, the National Electrical Code (NEC) Article 690 requires system grounding and monitoring for ground faults, when the maximum output voltage reaches a certain level, e.g., 50 V [10]. Also instead of three-phase utility connection, DE systems can also be connected to the single-phase utility, where the three-phase utility inverter has to be replaced by the single-phase inverter.

2.1. Photovoltaic systems

Photovoltaic (PV) technology involves converting solar energy directly into electrical energy by means of a solar cell. A solar cell is typically made of semiconductor materials such as crystalline silicon that absorb sunlight and produce electricity through a process called the photovoltaic effect. Individual solar cells are usually manufactured and combined into modules that consist of 36–72 cells depending on the output voltage and current of the module [11]. The distinction between modules and arrays is important when considering power electronics interfaces, as power electronics manufacturers design their products using either module-centric or array-based approaches. The power electronics topologies for the PV systems can be categorized on the basis of number of power processing stages, location of power decoupling capacitors, utilization transformers, and types of grid interfaces [6,12]. The two most common topologies are discussed next.

A centralized converter-based PV system is shown in Fig. 2. This is the most common type of PV installation in the past. PV modules are connected in series and/or parallel and the DC output of the PV array is connected across a filter capacitor. The output of the capacitor connects to the input of a voltage source three-phase inverter. The output of each phase of the converter is connected to an inductor and capacitor to limit the high-frequency harmonics injected into the AC system. A three-phase transformer is then used to connect the inverter to the utility providing voltage boost and galvanic isolation. The primary advantage of this design is the fact that if the inverter is the most costly part in the installed PV system, this is the least cost system design due to presence of only one inverter. The primary disadvantage of this configuration is that the power losses can be high due to the mismatch between the PV modules and due to the presence of string diodes [11]. Another disadvantage is that this configuration has a single point failure at the inverter, therefore it has less reliability [10].

To avoid the bulky low-frequency transformers, which are regarded as poor components mainly due to their relatively large size and low efficiency, the multiple-stage conversion systems are widely used in PV applications. The most common topology consists of a DC–AC grid-connected voltage source inverter along with DC–DC PV connected converters. A simple design for a multiple-stage PV inverter is shown in Fig. 3, which utilizes a high-frequency transformer included in the DC–DC converter. In general, the maximum power point tracking (MPPT) and voltage boost are done by the DC–DC converter controller and the power flow control to the utility as well as the sinusoidal unity power

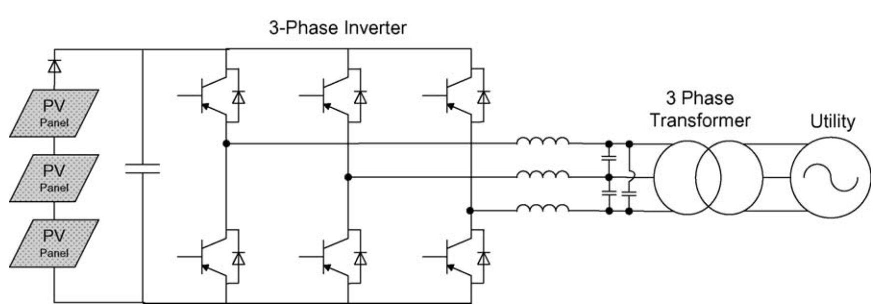

Fig. 2. PV system with three-phase centralized inverter.

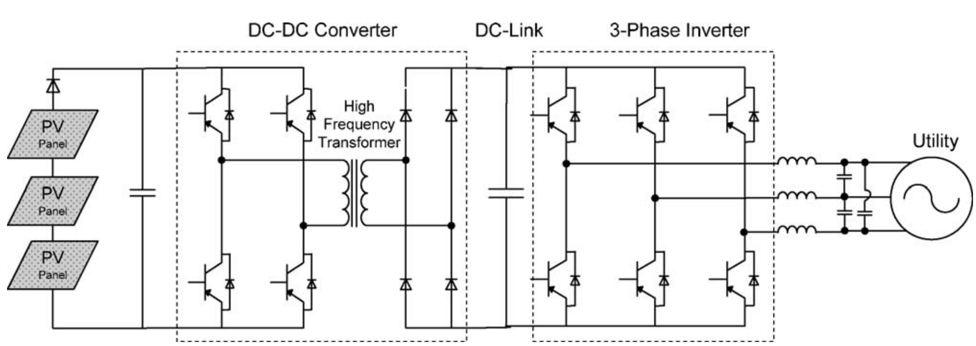

Fig. 3. PV system with high-frequency transformer based isolation.

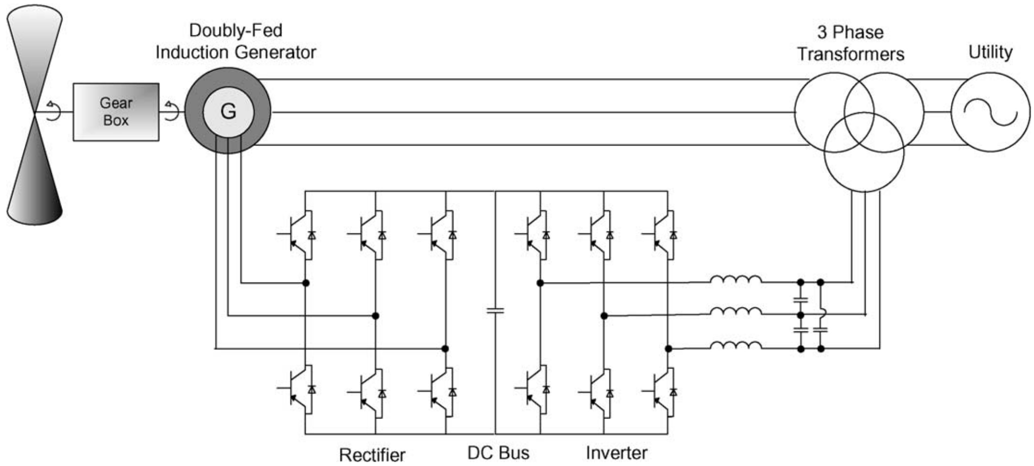

Fig. 4. Wind system with partially rated power electronics.

factor current injection to the utility are obtained by the DC–AC inverter controller [11].

2.2. Wind energy systems

Wind turbines convert kinetic energy in the wind into mechanical power that can be converted into electrical energy with a generator. The modern wind turbine technology can fundamentally be divided into three categories: the systems without power electronics, the systems with partially rated power electronics and the systems with full-scale power electronics for interfacing wind turbines [11].

The first type uses an induction generator; the wind turbine spins the rotor shaft of a squirrel cage-rotor induction generator connected directly to the grid without any PE interface. This wind turbine needs to operate at a constant speed (with an allowable variation of 1%–2%) and adjusts speed of the rotor by controlling the pitch of the wind turbine blades [11]. The induction machine requires reactive power to operate that can be either supplied from the utility grid or by capacitors connected at the machine terminals.

Another solution of using a medium scale power converter with a wound rotor induction generator, known as doubly fed induction generator (DFIG), is shown in Fig. 4. A power converter connected to the rotor through slip rings controls the rotor currents. This design does allow the wind turbine to have some amount of variable speed operation. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. The solution is naturally a little bit more expensive compared to the previous solution, however it is possible to save on the safety margin of gear, having reactive power compensation/production and more energy captured from the wind. This arrangement allows the generator stator winding to be undersized by about 25% with the power electronics making up the power difference from the rotor power [6,11].

A third type of wind turbine design uses a conventional or permanent magnet synchronous generator to convert the wind turbine power to a variable voltage, variable frequency output that varies with wind speed. A PE-based rectifier and inverter, as shown in Fig. 5, are then used to convert the full rated output of the machine to power that is compatible with the utility system. This design allows the wind turbine to operate in a variable speed mode which can allow more of the energy of the wind to be captured. Though diode bridges are often used as the rectifiers, due to cost considerations, self-commutated active rectifiers provide more flexible control [11].

2.3. Microturbines

Microturbines were developed by the industry through improvements in auxiliary power units originally designed for aircrafts and helicopters and customized for customer-site electric user applications. They can burn a variety of fuels including natural gas, gasoline, diesel, kerosene, naphtha, alcohol, propane, methane or digester gas. The majority of commercial devices presently available use natural gas as the primary fuel [9].

The shaft construction defines many important characteristics of the microturbine that eventually influence the required power electronics and control system. There are mainly two types of shaft construction, single-shaft and split-shaft [9]. In a high-speed single-shaft design, the compressor and turbine are mounted on the same shaft and the alternator rotates at speeds of 90,000–

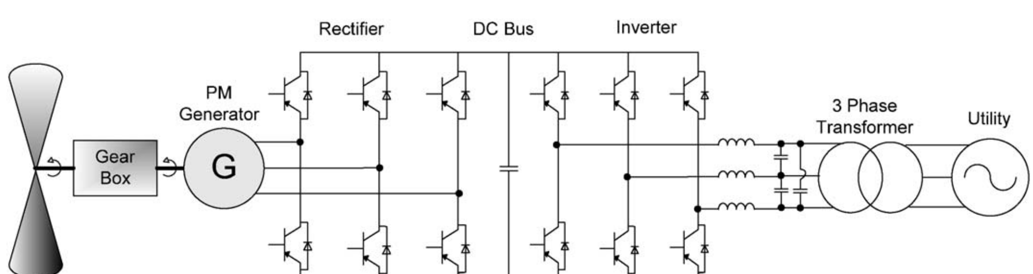

Fig. 5. Wind system with full-scale power electronics.

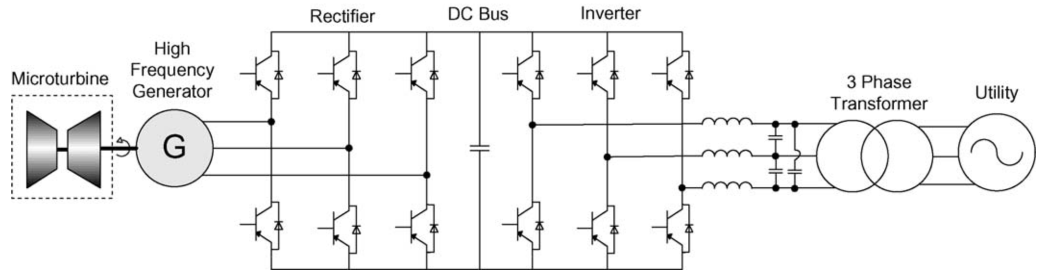

Fig. 6. Microturbine system with DC-link power converters.

120,000 revolutions per minute (rpm). The microturbine drives a high-frequency generator that may be either synchronous or asynchronous type [13]. The split-shaft microturbines are very different in terms of design and electrical power output. The split-shaft design has a power wheel on a separate shaft and transfers its output to a conventional generator using a gear reducer [9]. This system typically employs the two-pole generator sets running at 3600 rpm. Although the manufacturer claims that this type of microturbine does not need power electronics, it requires synchronizing equipment and relays for connection to the utility grid.

The most common power converter topology that is used for connecting microturbines to the grid is the DC-link converters [13]. The high-frequency power from the generator must be converted to DC first either by using diode-bridge passive rectifier or by self-commuted active rectifier. The DC-link is then used to construct three-phase voltages at 60 Hz using DC–AC inverter. Fig. 6 shows a microturbine generator feeding power to the utility by DC-link converters.

The main shortcomings of the AC–DC–AC conversion unit are large physical dimensions, high weight, and excessive volume/foot-print of the DC-link component, i.e. the DC capacitor (and if applicable the inductor) and the low reliability of the DC capacitor. To overcome these problems, a cycloconverter or a matrix converter can be used to connect microturbine generator to the grid instead of using rectifiers and inverters [14], as shown in Fig. 7. They are not yet commercial due to cost and technological issues associated with them [13].

2.4. Fuel cell systems

A fuel cell is an electro-chemical device that produces electricity without any intermediate power conversion stage. The most significant advantages of fuel cells are low emission of greenhouse gases and high power density. The energy density of a typical fuel cell is 200 Wh/l, which is nearly ten times of a battery. The efficiency of the fuel cell is also high in the range of 40–60%. If the waste heat generated by the fuel cell is used for cogeneration, the overall efficiency of such a system could be as high as 80% [11].

Fuel cells can be classified into five different categories based on the electrolyte chemistry, including proton exchange membrane fuel cell (PEMFC); solid oxide fuel cell; molten carbonate fuel cell; phosphoric acid fuel cell; and aqueous alkaline fuel cell. The PEMFCs are rapidly becoming the primary power source in movable power supplies and distributed generation (DG), because of their high energy density, low working temperature, and firm and simple structure [15].

Power generated by the fuel cell is DC, hence similar to a PV system, the power conditioning systems, including inverters are required in order to supply normal customer load demand or send electricity into the grid. The simplest form of fuel system power electronics configuration, as shown in Fig. 8(a), consists of a fuel cell followed by the DC–AC converter [16]. A DC–DC converter is usually put between the fuel cell and the inverter, as shown in Fig. 8(b). The DC–DC converter performs two functions, one is the DC isolation for the inverter, and the second is to produce sufficient voltage for the inverter input, so that the required magnitude of the AC voltage can be produced [16].

2.5. Internal combustion engines

Internal combustion (IC) engines burn liquid or gaseous fuels to convert chemical energy into mechanical energy in the form of moving pistons. The pistons then spin a shaft and convert the mechanical energy into electrical energy via an electric generator. IC engines can be of either spark ignition types that use natural gas, propane, or gasoline; or compression types that use diesel or heavy oil [9].

Typically most IC engines are interconnected to the utility through a fixed speed synchronous generator that has protective relays. In automotive application, it has been shown that the torque curve of a diesel engine is optimized for high power versus

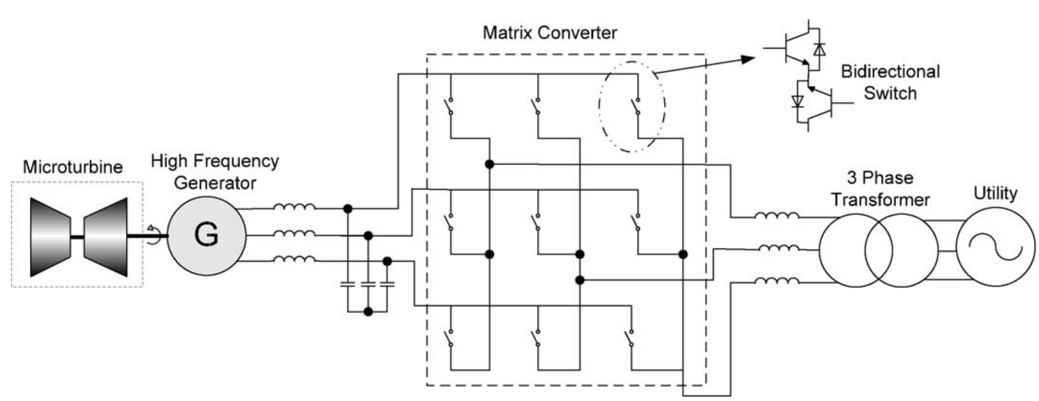

Fig. 7. Microturbine system with matrix converter.

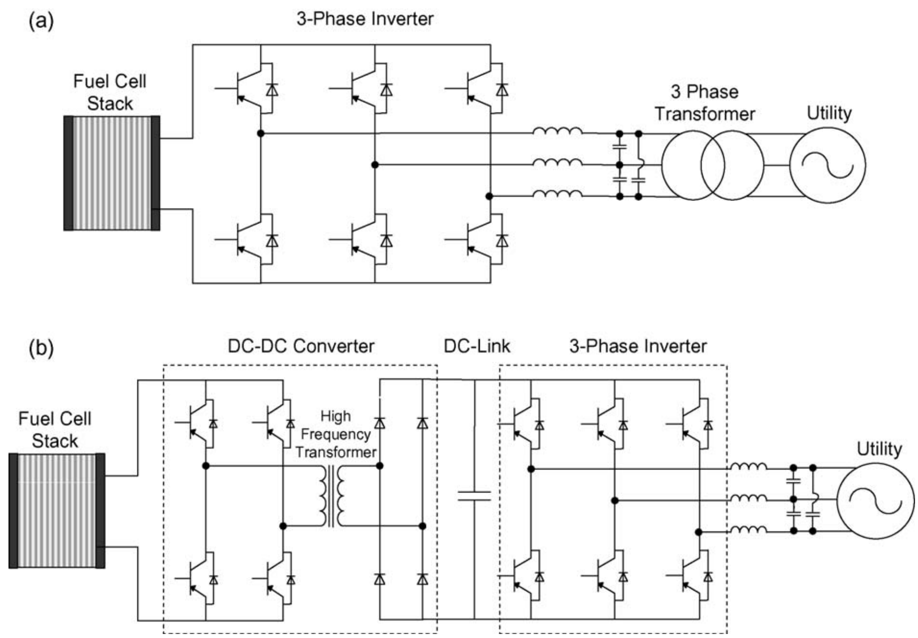

Fig. 8. Fuel cell system with (a) single inverter and (b) inverter and isolated DC–DC converter.

speed performance over the range 1000–3600 rpm. But for power generation and direct utility connection, the generator speed must be constant for 60 Hz systems, depending on the number of generator poles. Therefore, conventional IC engines do not utilize the full speed range of the engine on the application or removal of electrical loads. Using a power electronics interface with an IC engine offers the advantage of having variable speed operation of the IC engine which in turn optimizes fuel usage for varying loads [17].

The variable speed IC engine-generator configuration can be of different types depending on the generator. The basic power electronics designs are similar to the power electronics topologies used with wind system. For synchronous generator or cage induction generator, variable voltage, variable frequency output is converted to the 60 Hz utility compatible AC by using back-to-back rectifier-inverter configurations, similar to Fig. 5 [17]. Also the doubly-fed induction generators and associated power electronics can also be used (as shown in Fig. 4) [18].

2.6. Battery energy storage systems

Lead-acid batteries are the prevalent form of electrical energy storage in use today. They have a commercial history of well over a century, and are being applied in every area of the industrial systems including telecommunication, emergency power, and auxiliary power in stationary power plants. Because of their low cost and ready availability, lead-acid batteries are typically the default choice for energy storage in any new applications. This popularity comes despite many perceived disadvantages, including low specific energy (W h/kg) and specific power (W/kg), short cycle life, high maintenance requirements, and environmental hazards [19]. Other types of batteries, such as zinc-bromine flow batteries, vanadium redox batteries, sodium sulfur batteries and nickel-electrode batteries are also shown promise for future electrical storage applications [19].

All of the battery technologies produce DC that must be converted to AC power to connect to the utility. The individual battery cells are generally connected in different configurations in series and/or parallel to achieve the required voltage and current outputs. The power conditioning systems, including inverters and DC–DC converters, are often required for the battery energy storage systems (BESSs). The most unique aspect to power electronics for BESS is that they must be bidirectional, that is both taking power (during charging) and providing power (during discharge) from/to the grid. Unlike PV and fuel cell inverters, however, BESS inverters are not expected to consider the peak power operations. They only provide the power level demanded by the system that can be sustained by the battery [9].

The simplest form of battery energy storage system configuration, as shown in Fig. 9, consists of a BESS followed by DC–AC converter. If the isolation or a high voltage conversion ratio is required, a transformer is usually integrated into the system [20].

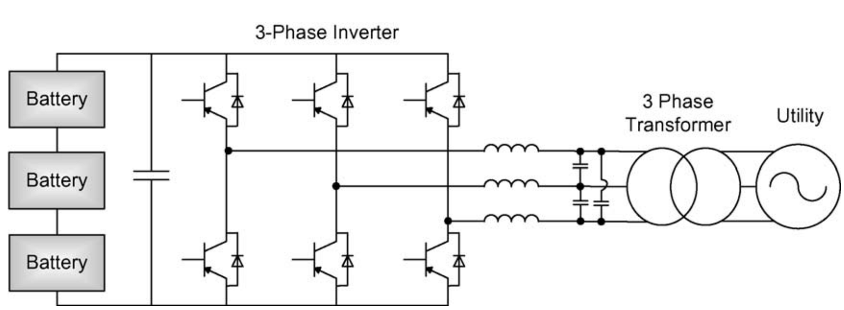

Fig. 9. BESS with single inverter configuration.

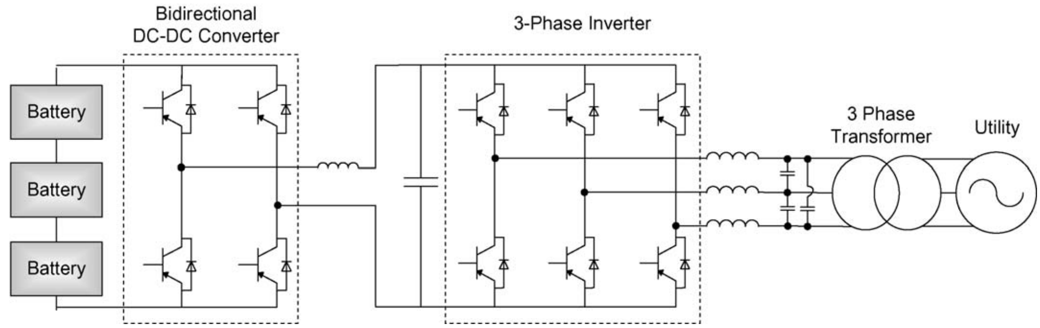

Fig. 10. BESS with bidirectional DC–DC converter and inverter.

The most common two-stage topology for the BESS consists of a DC–AC inverter with a bidirectional DC–DC converter. A simple design for a two-stage power electronics topology is shown in Fig. 10. In that figure, a full-bridge DC–DC converter is used that can operate with any voltage and current polarity. The voltage polarity and amplitude can be set irrespective of the current direction [21].

All the BESS power electronics topologies discussed so far has no isolation present in them. For utility connection, therefore, a line-frequency transformer is used for galvanic isolation. To avoid the bulky line-frequency transformers, several bidirectional isolated DC–DC converter topologies has been developed [22,23]. One such DC–DC topology is given in Fig. 11 that can galvanically isolate the output terminals from the input terminals, and can step up and down its output voltage by using a high-frequency transformer [22]. This topology is not very economical due to large device counts.

2.7. Flywheel energy storage systems

Flywheels are very popular as energy storage due to the simplicity of storing kinetic energy in a spinning mass. Conversion from kinetic to electric energy is accomplished by electromechanical machines. The key is to match the decreasing speed of the flywheel during discharge and the increasing speed during charging with a fixed frequency electrical system [9]. Along with electromechanical machines, two methods are used to match system frequencies, mechanical clutches and power electronics. The basic operation for a flywheel can be summarized as follows. When there is excess in the generated power with respect to load demand, the difference is stored in the flywheel that is driven by the electrical machine operating as a motor. On the other hand, when a fluctuation in delivered power is detected in the loads, the electrical machine is driven by the flywheel and operates as a generator supplying needed extra energy.

The flywheel energy storage systems (FESSs) can be classified into two categories. The first technology is based on low-speed flywheels (up to 6000 rpm) with steel rotors and conventional bearings. The second one involves more recent high-speed flywheel systems (up to 100,000 rpm) that are just becoming commercial and make use of advanced composite wheels that have much higher energy and power density than steel wheels. This technology requires ultra-low friction bearing assemblies, such as magnetic bearings; and the most current researchers are involved in this design [6,12].

The most common configuration for supplying flywheel energy to the grid is the back-to-back converter as shown in Fig. 12 [24]. The variable frequency AC output of the flywheel generator is first converted to DC power. The DC bus is then connected to a DC–AC converter for connection to the grid. During charging, the grid-

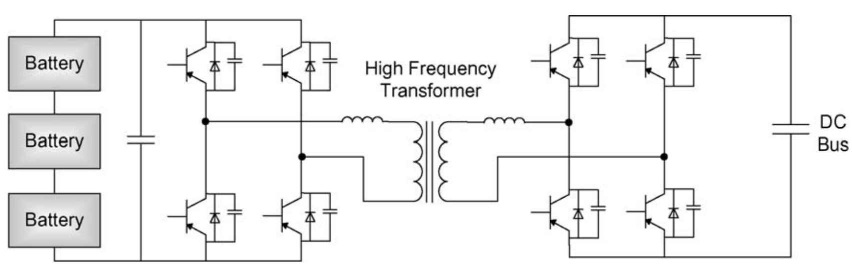

Fig. 11. Bidirectional isolated DC–DC power electronics topology.

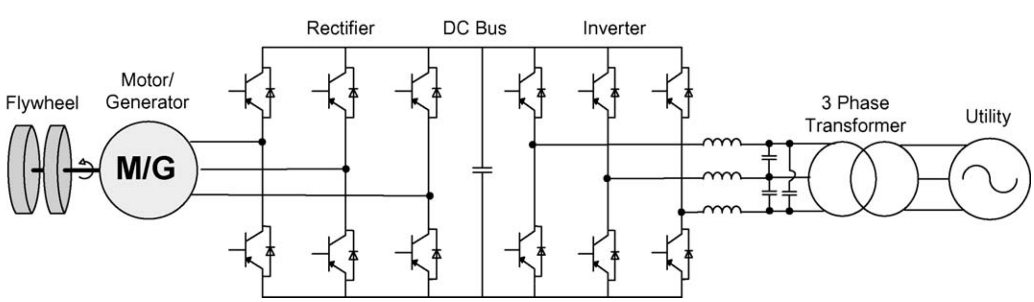

Fig. 12. FESS with DC-link power converters.

connected converter works as rectifier and the generator connected converter works as the inverter. During discharge, the two converters exchange their roles to supply power from FESS to utility.

3. Modular power electronics interfaces

From the previous sections of this paper it is evident that the power electronics is an essential component for converting generated power into useful power that can be directly interconnected to the utility grid. Because of the similar functions of these power electronics capabilities, the development of a power electronics interface (PEI) that is scalable to meet different power requirements, with modular design, lower cost, and improved reliability, will improve the overall cost and durability of distributed and renewable energy systems.

3.1. Integrated power electronics modules

The modular design approach for the PEI revolves around the advanced power electronics devices in form of integrated power electronics modules. Power electronics devices evolved tremendously from their familiar plastic package form towards integrating more and more components into a module. The module package initially combined discrete switching devices to form a half-bridge, then evolved to include full-bridge circuits, three-phase bridges (six-packs) and, more recently, gate drives and sensors. Integrated power electronics modules (IPEMs), such as the Semikron Advanced Integration (SKAI) modules or PM1000 by American Superconductor, have also recently come on the market [6]. In this approach, along with the power electronics devices; DC-link filter capacitors, current and temperature sensors, gate drivers, heat sink and optional digital signal processing (DSP) controller are combined into a single highly optimized module. The DSP based local controller can communicate with a higher level controller through different communication interfaces.

The power electronics devices can be configured in different ways inside the IPEM. Some manufacturer products based on half-bridge power modules, where each of the half-bridge can be considered as the PEBB with their own hardware controller (or hardware manager) and sensors. Also IPEM with three-leg, six switches configurations is also available in the market [6]. In any case, it is important to note that the IPEM concept goes beyond just power module structures, and it also includes integration of sensing and control with the implementation of auxiliary functions. The structure of a representative IPEM is shown in Fig. 13 [25].

This particular IPEM consists of six IGBT switches arranged in three-phase bridge format. The DC bus filter capacitor, voltage and current sensors, auxiliary power supply, gate drivers are all included inside the IPEM having a common heat sink. A local DSP controller can also be included inside IPEM depending on the user's preference for application level of control.

3.2. Modular PE topologies for DE systems

From the discussions presented earlier, it can be observed that the most generalized and efficient power electronics topology for photovoltaic (PV) and fuel cell systems is the isolated DC–DC converter cascaded with DC–AC inverter. The wind, microturbine systems generate variable frequency AC output which needs to be converted into 60 Hz AC for utility connection. The use of back-to-back converter is the most efficient way to utilize the generated power from wind and microturbine systems. Typically most internal combustion (IC) engines are interconnected to the utility through a fixed speed synchronous generator, but as discussed in Section 2.5, using a back-to-back voltage source converter with an IC engine offers the advantage of having variable speed operation

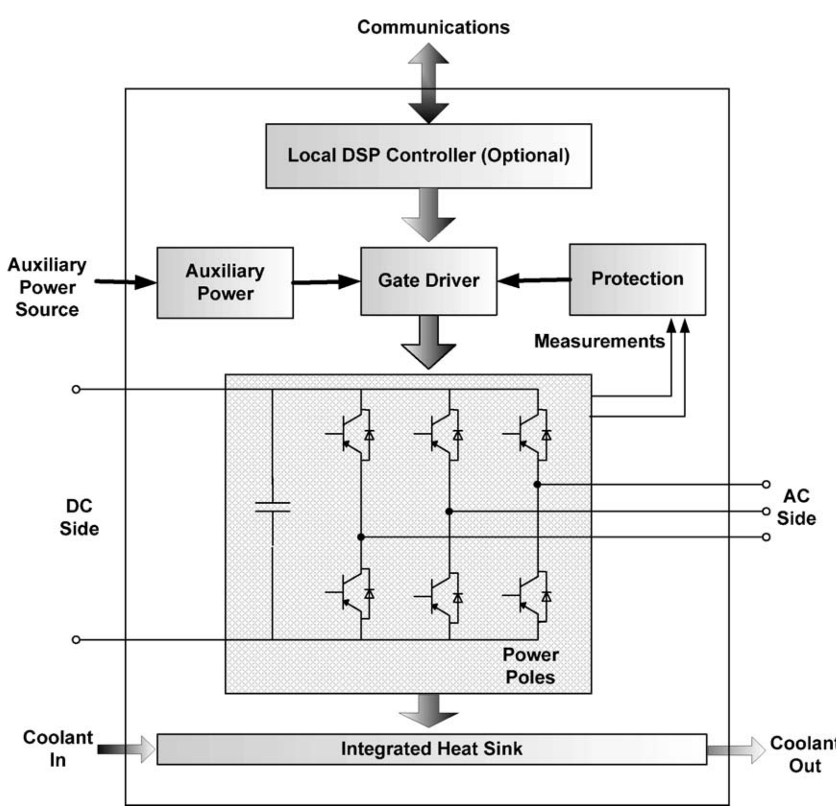

Fig. 13. A typical integrated power electronics module.

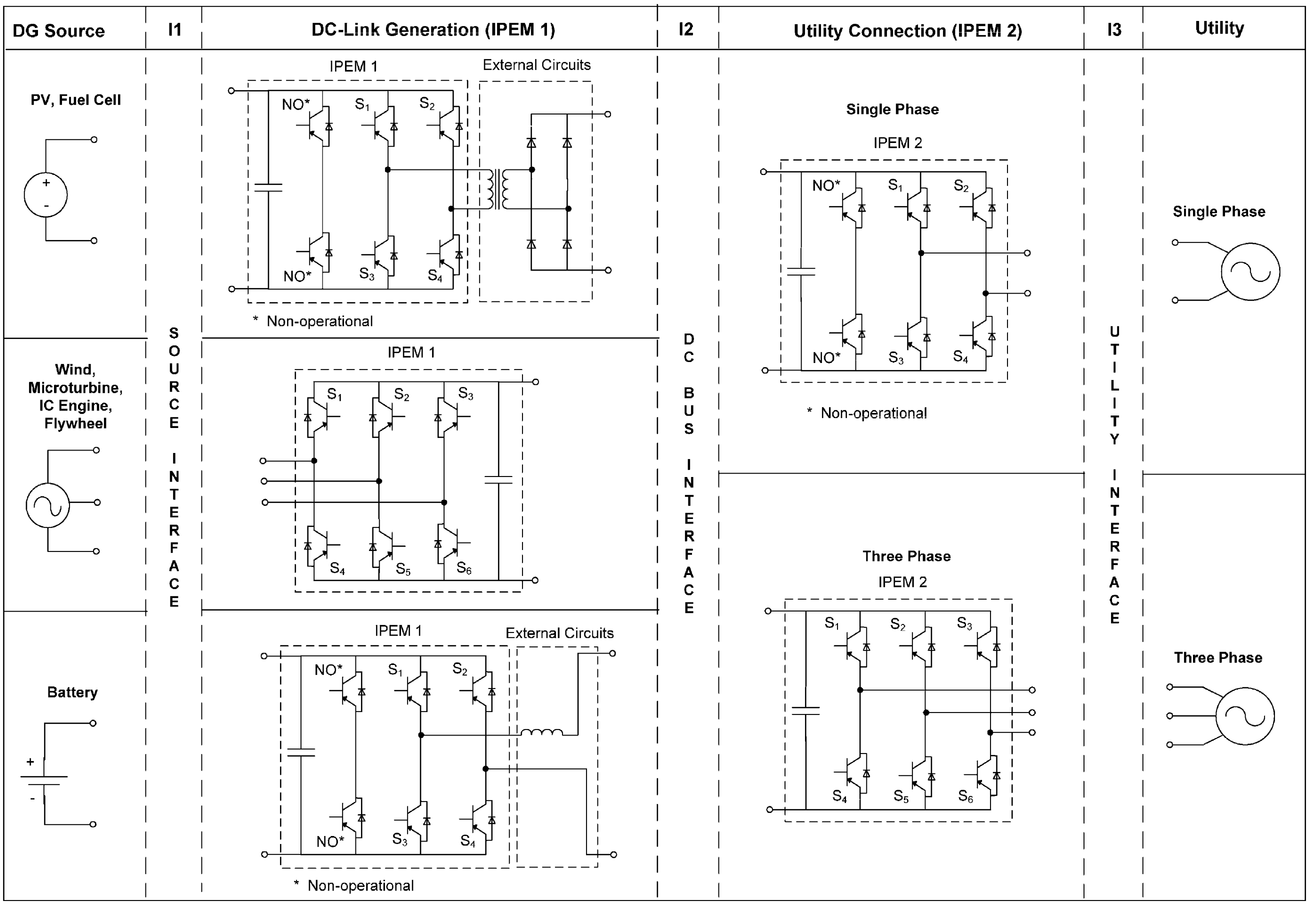

Fig. 14. Generalized IPEM-based power electronics for different distributed energy systems.

which in turn optimizes fuel usage for varying loads. Depending on the type of storage, bidirectional power electronics converters are required for utility connection. For battery energy storage system (BESS), a bidirectional DC–DC converter followed by a DC–AC inverter is the most general choice, whereas for the flywheel system a back-to-back converter can be utilized for utility connection. A diagram showing the use of IPEM with different distributed generation system is given in Fig. 14.

In Fig. 14, two IPEMs are used for the distributed energy systems. Each of the IPEMs include six IGBTs along with gate drivers and sensors as discussed in the previous subsection. In some cases, additional hardware components are required for designing the converter. Also, three power interfaces are shown in Fig. 14 that are essential for the operation of the complete system. The source interface for such systems typically consists of EMI filters and the utility interface includes the line-frequency filters. The DC bus filter may also be required if the capacitor inside the IPEM is not sufficient. For the isolated DC–DC converters with PV and fuel cell systems, the IPEM-based solution is not optimal, as one-third of the switches are not used in the H-bridge configuration. However, the IPEMs offer cost savings due to the commonality of the hardware and short development time for the system [6]. For the power electronics topologies with wind, microturbines, IC engine and flywheel systems, the high-frequency isolation is not feasible. Hence the line-frequency transformers are often included in utility interface for galvanic isolation [6]. The power electronics for the battery energy storage system (BESS) consists of a full-bridge DC–DC converter can operate with any voltage and current polarity. In this topology, a line-frequency transformer is included for galvanic isolation [6].

The most common power electronics part of each of the DE systems is the utility connected inverter. Depending on utility connection type, this inverter can be of single-phase or three-phase. As can be observed from Fig. 14, the single-phase inverter uses only four IGBT switches out of six available ones, hence not optimized. The IPEMs offer cost savings due to the commonality of the hardware.

3.3. Controller for PEI systems

Use of dual converters for the DE systems also provides the flexibility of designing different control objectives. In general, the source connected converters are used for DC bus voltage control, but their applications can vary from one system to the other. For example, in PV systems, the source converter is often controlled to achieve maximum power point tracking (MPPT) [10]. Similarly, in wind systems, the control of the source converter is frequently used for controlling generator speed, current and flux [26].

There are two basic control modes for the grid-connected converters: constant current control and constant power control. It is debatable whether an inverter should be allowed to regulate voltage during grid-connected operation. The current IEEE 1547 Standard does not allow distributed generation to actively regulate voltage, while some people in the industry suggest that the voltage regulation may have some positive impact on the grid [27]. In the constant current control, the current injected to thse utility is controlled based on a predefined current reference. For the constant power control, the active and reactive power output of the inverter is controlled. In some cases, the reactive power reference could be a power factor reference [27]. Also a variation of the constant power control is frequently used for grid-connected converters. Instead of using the active power reference, a DC bus voltage is regulated, while the input to the converter is a constant

Table 1
Typical control functions with IPEM-based power electronics.

DE systems	Control functions		
	IPEM 1	IPEM 2	Additional
PV	Maximum peak power tracking	Power flow to grid	n.a.
Wind	Generator speed, current, flux	DC bus voltage, current to utility	n.a.
Microturbines	DC bus voltage	Power flow to grid	Fuel usage
Fuel cell	DC bus voltage	Power flow to grid	Fuel usage
IC engine	DC bus voltage	Power flow to grid	Fuel usage
Battery-charging	Battery terminal voltage	DC bus voltage	Operational mode
Battery-discharge	DC bus voltage	Power flow to grid	Operational mode
Flywheel	Generator torque, speed, DC bus voltage	Power flow to grid	n.a.

power source to represent the prime mover. In this case, the output of the DC bus regulator is proportional to the active power. The increase of DC bus voltage means the charging of the DC capacitor, hence it can be concluded that the power from the prime mover is increasing. In order to maintain the DC bus voltage, the converter output power is to be increased so that the power can be transferred to the utility [27].

Additionally, for the fuel based systems, such as microturbines, fuel cells and IC engines, external controller can be designed for optimization of fuel based on the system states [6]. In Table 1, some typical control functions are shown for different distributed energy systems. These control functions are to be implemented for the PEI systems either by using the local DSP controller or by utilizing CPU based higher level controller and the communications.

4. Standardization of interfaces

In traditional centralized digitally controlled power electronics systems, construction, debugging and maintenance of the PE systems are complicated and difficult due to lack of standardization and modularization, and also because of the strong dependence of control design on system hardware. The concept of power electronics building blocks (PEBBs) provides a way to hardware standardization of power electronics systems. Based on PEBB concept, the new integrated devices are feasible for distributed energy applications as discussed in the previous section. In addition to that, standardization in power electronics requires standardizing the power flow and signal distribution network, which in turn allows for distributed controller approach. The standardization of communication interface allows division of power electronics system into flexible, easy-to-use, multifunctional modules or building blocks, which can significantly ease the task of system integration. By using control software that is functionally divided into hierarchical levels and by standardizing interfaces between levels, the application software becomes independent of the hardware specifications of power stage and products from different vendors can communicate and work with each other [8]. Furthermore, if both sides of an interface support device self-identification and system resources assignment, then the so-called plug-and-play implementation is feasible for future PEI systems.

4.1. Power interfaces

From the generalized IPEM-based power electronics for different distributed energy systems, as shown in Fig. 14, following characteristics should be made available for designing the standardized power circuits:

- Each IPEM should have two ports named DC port and AC port. Port and AC Port.
- Both ports for the IPEM are to be bidirectional and should be able to work as buck or boost mode.
- Device ratings for the IPEMs are limited by manufacturer datasheet. Therefore for high power applications, paralleling of the converters are necessary.
- The wiring will be based on the operational power.
- Filters, transformers and other external circuits design will be dependent on the operational power. It is always possible to design the circuit for higher power and use it for low power applications, but obvious drawbacks will be inefficient design and higher cost.
- Combining multiple sources and/or storages can be done using the DC bus. In such case, a single IPEM can be used for DC–AC inversion [28].

4.2. Control interfaces

For the modular design of the power electronics for distributed generation applications, the control of the PE system can be functionally divided into hierarchical architecture as shown in Fig. 15. The controller that is the inherent part of the IPEM is defined as local controller. In literature it is often called as hardware manager [29,30]. The higher level controller is defined as application manager. This is the controller external to the IPEM that establishes the functions that are the main mission of the power electronics system. In order to achieve the goals required at the system control level, some standard control functions must be performed inside applications manager [6]. If more than one application is combined, for example in a hybrid system with different DE sources, a higher level system manager is required that coordinates the operation as well as maintains the system data bus for communicating with the individual application managers [6].

The local controller is designed to provide control and communication functions for the IPEM it is associated with. It is designed to support all module specific control tasks thus making the module specific functions, such as for example soft switching, invisible to the application manager. As the IPEMs provide enough calculation capabilities due to the built-in DSP module, it is preferred to carry out the voltage and current control inside the local controller in addition to the PWM generation for the switches. From a generalized evaluation of different converters, it can be found that there is a set of common functions shared by all of them and also these common functions are related to the lower levels [30]. For DE applications, the PWM generation at the lower level always relates to either voltage or current control for the particular converter. Hence it is desirable to achieve these controls inside the local controller to make the system more modularize [6].

In addition, the local controller can be used for over-current protection and indication; current, voltage and temperature sensing with A/D conversion; and communication of PWM, status and measurements. Some IPEM manufacturer also offers the IPEM without the DSP controller, which in turn provides the user greater flexibility of choosing suitable DSP depending on the application

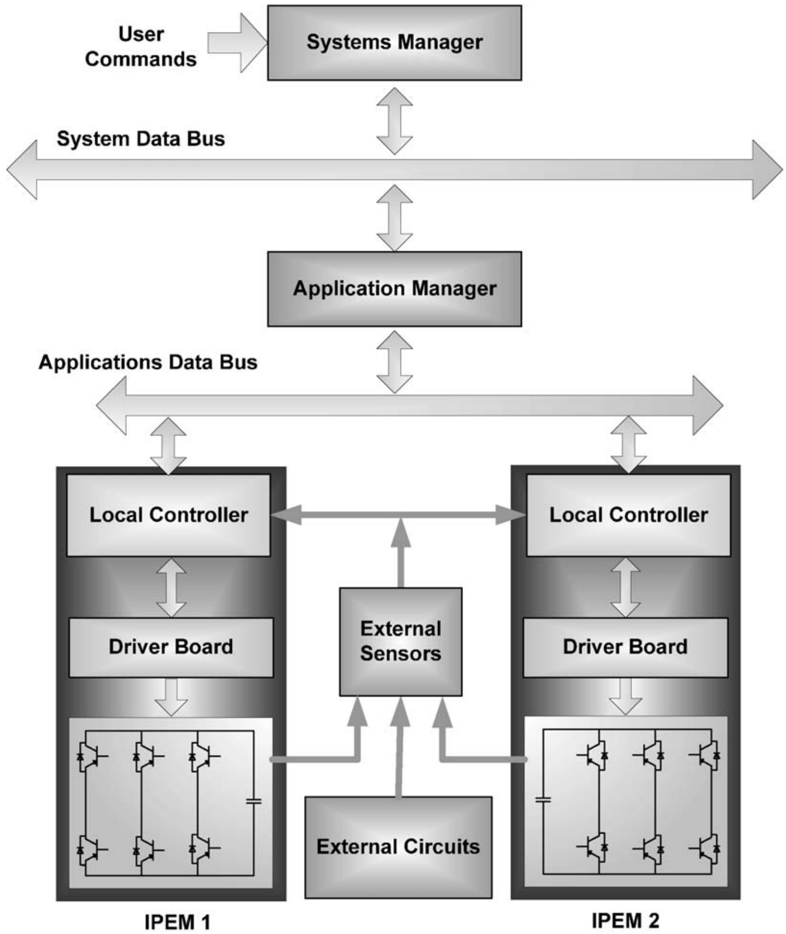

Fig. 15. Hierarchical division of control functionalities for IPEMs.

requirements. In such cases, it is required to define the interfaces for the local DSP controller to maintain the modularity and standardization for the IPEM system [6].

The application manager is the external controller that operates to establish the functions that are the main missions of the power electronics system [6]. For example, in microturbine applications, the power circuit consists of two IPEMs connected in back-to-back formation having a common DC bus. The application manager operates the individual local controllers in such a way that the source IPEM (IPEM 1) works for DC-link voltage control and the utility IPEM (IPEM 2) controls the power flow to the grid. In order to achieve these goals required at the system control level, some standard control functions must be performed in the application manager. The application manager controls the local controller through standard interfaces. It also controls the communications data bus for the local controllers.

Table 2
Input–output signals and control interfaces for hierarchical controller in an IPEM.

IPEM	Interface 1	Local Controller (LC)	Interface 2	External controllers (EC) and external sensors (ES)
Inputs PWM signals (5V CMOS level) Enabling signals Outputs DC bus voltage Phase currents Heat sink temperature Fault signals 1. Excessive switch current 2. Phase over-current 3. DC bus over-voltage 4. Power supply under-voltage 5. Over-temperature at heat sink	⟺ D-sub 25 p in connector with ribbon cable	Inputs Phase currents Phase voltages DC bus voltage Heat sink temperature Relay sense signals Encoder inputs Zero-crossing detection	⟺ Measurement signals from sensors to analog input of DSP	Inputs Measurement signals from LC Measurement signals from ES Encoder signals Fault signals User Inputs PWM status signals
		Fault signals from IPEM System operation mode signals from EC Protection signals from EC Outputs Gate drive PWM signals Communication signals for IPEM Enabling signals to IPEM PWM status signals to EC Fault signals for EC	⟺ Control signals from external controller by CAN or asynchronous serial	Outputs Reference voltage and current signals to LC Communication signals for external data bus Relay contactor signals Protection signals to LC System operation mode signals to LC

The top level system manager performs the controls tasks at the system level, such as responding to users' commands, coordinating performances between different applications, and monitoring system execution [6]. Additionally, the system manager can be utilized to determine the mode of operation for each of the DE systems individually so that the issues related to islanding and energy cost optimization can be resolved.

The input–output signals and control interfaces for a typical IPEM hierarchical controller are summarized in Table 2. For this particular IPEM, it is assumed that the local DSP controller is outside the power electronics module. Furthermore, it is assumed that the output of the external sensors is connected directly to the local controller's analog input ports. The connection between the local controller and the applications manager is assumed to follow typical IPEM manufacturers Controller Area Network (CAN) or asynchronous interface [6]. But different open architecture communications protocols can also be used as will be discussed later. Both the system manager and application manager is developed in CPU and named as external controllers in the table. All the measurement signals are routed to the external controllers via local controller.

The communication between the IPEM and local DSP controller is obtained through a D-sub 25 pin connector with ribbon cable. If the DSP controller is inside the IPEM, this communication interface is not available to the user. The application manager and the system manager are generally implemented in CPU. The communications between the local controller and the CPU is typically achieved by CAN or asynchronous serial using fiber optics. From [30], it can be observed that the bandwidth of the analog type signals depends on number of signals; switching frequency; and number of bits representing the duty cycle. Analog signals that are not directly related to the switching frequency may require a lower bandwidth. On the other hand, the channel bandwidth requirement for the digital type signal depends on number of signals; ratio of sampling period to transmission time; sampling frequency; and number of bits representing the variables. In most of the APEI applications, the CAN communication is sufficient for data transmission as it can support up to 1 Mbit/s bit rate at network lengths below 40 m. But using IPEMs for other type of applications such as active filtering may require new communication protocols as described in [29,30].

5. Conclusions

Although power electronics (PEs) are the integral part for most of the distributed energy (DE) systems to convert power generated into useful power for grid-connection and consumer use, they can add a significant installation costs for DE system. In addition, they are often the least reliable part in the whole DE system design. Consequently, from the commercialization perspective, the key business needs for DE power electronics are reducing costs and improving reliability.

There are many PE topologies that are being used by the distributed energy resource community as discussed in this paper. Though most of the power electronics designs are specific to the DE technology, they possess some common functionality across the technologies. It is therefore feasible to design a modular and scalable power electronics interface (PEI) that will allow each of the energy source technologies to use the same power electronics components within their system architectures thus allowing for cost reduction due to high volume production of the PEI modules. This modular block approach will also help manufacturers to use their products without sacrificing their intellectual property. On the reliability perspective, as the module integrates many of the subcomponents means that the user is getting a fully integrated and tested package, a package that is already qualified to meet some of the stringent specifications and therefore highly reliable. The integrated power electronics module (IPEM) based back-to-back converter topologies has been presented in this paper as a viable PE interface that can operate with different DE systems with small or no modifications.

However, to reach the goal of modularity, some challenges must be overcome first. One challenge lies in defining the power and communication interfaces. The power connection interfaces must be simple enough for the common consumers to accomplish installation. Standardization is also required for the communication interfaces between modules, packages and controllers. IEEE standards do not currently address this issue, and there is no standard for communication between different products. To address the standardization issues, a control structure that is functionally divided into hierarchical levels is discussed in this paper. The standardized interfaces that are required between levels are also pointed out. By utilizing the proposed control structure, the application software will becomes independent of the hardware specifications of power stage; and products from different vendors can communicate and work with each other. Further research and development is necessary to expand requirements and implement proposed modular power electronics associated with distributed energy interconnection with utility grid.

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